A simplified Approach to integrate Energy Calculations in the Life Cycle Assessment of Neighbourhoods

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ABSTRACT

Life Cycle Assessment (LCA) is a method which can be used to effectively evaluate and optimize the environmental impact of the built environment. However, when carrying out an LCA on the neighbourhood scale, estimating the energy consumption in buildings is problematic because most energy simulation tools require a lot of input data, which are not available in the master planning stage. This paper proposes a simplified approach to evaluate the heating energy consumption in neighbourhoods, taking into account the neighbourhood layout and shading caused by interacting buildings. The proposed approach, which is implemented for the Belgian context, is a refinement of the existing Equivalent Degree Day (EDD) method, by including results from both semi-dynamic and dynamic solar gain calculations. To illustrate this new approach, a parametric neighbourhood model is developed, linked to the energy simulation software EnergyPlus and LCA calculations. Simulations of a medium-density urban block reveal substantial differences in heating energy consumption, depending on shading patterns, confirming the importance of integrating simple but reliable energy calculations in neighbourhood LCA.

1. INTRODUCTION AND OBJECTIVES

In order to move towards a more sustainable built environment, new urban developments need to be planned and organized differently. As shown in previous studies (Trigaux, Allacker, & De Troyer, 2014) (Herfray, 2012), life cycle assessment (LCA) is a method which can be used to effectively evaluate and optimize the environmental impact of buildings and neighbourhoods. However, when carrying out an LCA on the neighbourhood scale, estimating the energy consumption in buildings is problematic, especially for passive and low energy design.

To date, most building energy simulation tools require a large amout of data, which is unavailable in the early stage of the design process. Although technical aspects are often not considered during the master planning stage, decisions related to the neighbourhood layout, building compactness and solar shading can also affect the heating energy demand importantly. Therefore a fast but reliable energy calculation method is needed, taking those aspects into account.

This paper proposes a simplified approach to evaluate the heating energy consumption in neighbourhoods during the master planning stage; which can be integrated in an LCA study. The proposed approach is based on the Equivalent Degree Day (EDD) method (Diensten voor de programmatie van het wetenschapsbeleid, 1984), giving a first estimation of the heating energy demand. In order to accurately consider the impact of solar gains and shading caused by interacting buildings, the original method is refined, using results from both semi-dynamic and dynamic solar gain calculations.

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This new method, further referred to as dynamic Equivalent Degree Day method, is illustrated based on a parametric neighbourhood model linked to the energy simulation software EnergyPlus (U.S Department of Energy, n.d.). The energy calculations are moreover integrated in a broader LCA study.

In the subsequent section the methodological aspects are described, focussing on the Dynamic EDD method and the LCA. In section 3 the parametric model is described and used to analyse the energy consumption and life cycle environmental impact of a medium-density urban block. Conclusions and recommendations are drawn in the final section.

2. METHODOLOGY

From the Degree Day method to the dynamic Equivalent Degree Day method

The Degree Day (DD) method is an existing method to estimate heating requirements in buildings, when no layout decisions are taken. The basic assumption is that the yearly heating demand at a specific location is proportional to the number of DD (°d) at that location (Diensten voor de programmatie van het wetenschapsbeleid, 1984a). For each day of the heating season, the difference between the average indoor temperature (T_i) and average outdoor temperature (T_e) is calculated. The sum of all these daily temperature differences over the whole heating season results in the number of DD. This is illustrated in **Figure 1** with the DD 15/18 for the temperate Belgian climate. In this specific case it is assumed that no heating is required when the daily average outdoor temperature is higher than 15°. Furthermore, a fixed average indoor temperature of 18°C is considered. In **Figure 1**, the number of DD is represented by the surface enclosed by the indoor and outdoor temperature curves and the lines delimiting the heating season. For practical reasons, this surface is approximated using monthly average outdoor temperatures, as illustrated by the hatched surface in **Figure 1**. In this paper, 2738°d are calculated as representative for the Belgian climate, based on the EnergyPlus test reference year for Brussels.

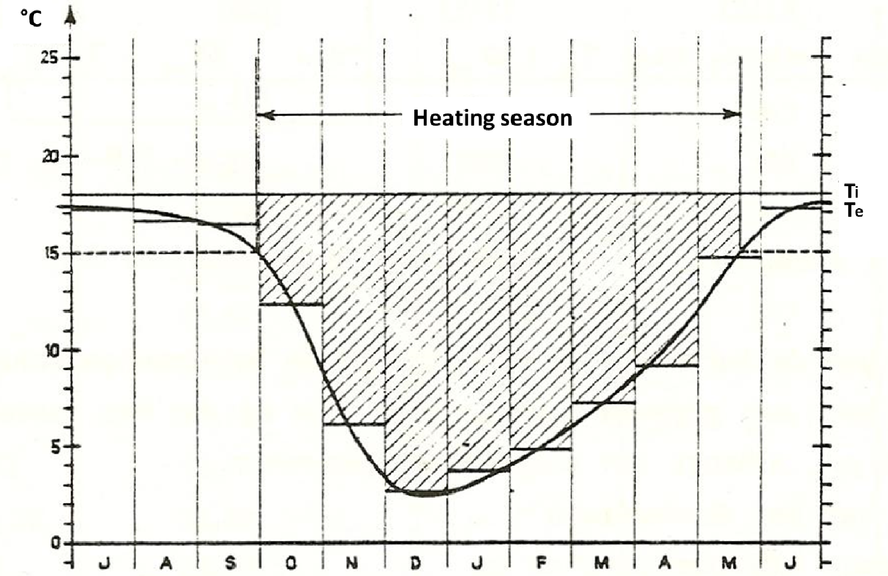

Figure 1 DD 15/18 for the temperate Belgian climate (Diensten voor de programmatie van het wetenschapsbeleid, 1984a, p.33).

Based on the number of DD, the heating energy demand (Q_j) is estimated using **Formula 1** (Diensten voor de programmatie van het wetenschapsbeleid, 1984b, p.39), which includes the impact of heat transmission losses through the building skin and heat ventilation losses:

$$Q_j = (U_m * S + V * n * 0.36) * 3600 * 24 * {}^\circ d \qquad (1)$$

With:

- U_m = average heat transfer coefficient (W/m²K)
- S = heat loss surface (m²)
- V = inside building volume (m³)
- n = air change per hour (1/h)
- °d = number of Degree Days

The Equivalent Degree Day (EDD) method is a refinement of the DD method, as the latter often leads to an overestimation of the heating demand (Diensten voor de programmatie van het wetenschapsbeleid, 1984b). Internal heat gains (resulting from people, electric devices and artificial lighting) and solar gains, which are not considered in the DD method, often result in a reduction of the heating demand, especially in well-insulated buildings. For this reason, the DD method was refined by defining EDD (eq d°). EDD (**Figure 2**) are calculated based on two temperature curves: the temperature curve of no more heating (T_{NH}) and the temperature curve without heating (T_{WH}). The first one (T_{NH}) is defined as the indoor temperature above which no heating is required. This T_{NH} is lower than the original indoor temperature of 18°C, since the internal gains will be sufficient to compensate the heat losses. The second temperature curve (T_{WH}) is the increased indoor temperature, resulting from solar gains, when the building is not heated and not occupied.

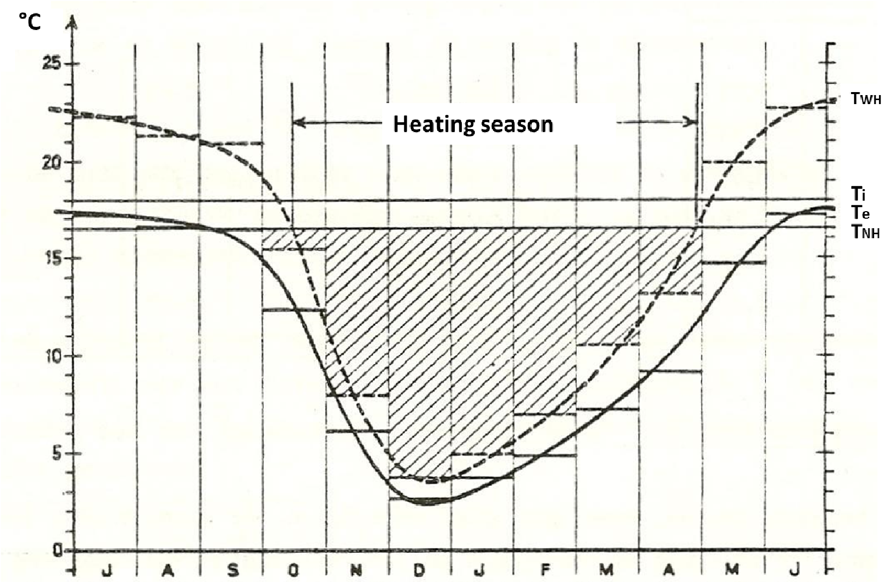

Figure 2 Equivalent Degree Days 15/18 for the temperate Belgian climate (Diensten voor de programmatie van het wetenschapsbeleid, 1984a, p.36)).

The T_{WH} is hence calculated, based on the useful solar gains in a building. These solar gains can be estimated by using several approaches, ranging from static to dynamic simulations. In the original EDD method, a static approach was followed, based on average solar radiation data for two characteristic months of the year (respectively March and December) (Diensten voor de programmatie van het wetenschapsbeleid, 1984b). In previous research, Allacker (Allacker, 2010) determined an average of 1200 eq d° for residential buildings in the Belgian context, based on an analysis of two dwelling types, and for several insulation levels. The calculation of this average EDD was based on the Flemish Energy Performance of Buildings (EPB) regulation (Flemish Government, 2005). This estimation is used in the analysis (section 3) as a reference base for the more dynamic calculations (see next paragraph).

This paper proposes a new method, the dynamic Equivalent Degree Day method, based on two more dynamic solar gain calculations. Firstly, a semi-dynamic calculation was made based on the Flemish EPB regulation (Flemish Government, 2005). In this first approach, a characteristic day of each month is considered and shading patterns, resulting from neighbouring buildings, trees, sheds or side walls, are approximated by defining a set of obstruction and overhang angles per window. For each window those angles are then projected on the visible part of the sky dome to calculate the reduction in direct solar radiation, compared to unshaded conditions. As illustrated in **Figure 3** for a dwelling in a rectangular urban block, this approximation can lead to an overestimation of shading patterns and thus lower solar gains than in reality. Secondly, a dynamic energy caculation, using the the software EnergyPlus, was made to calculate the indoor temperature without heating (T_{WH}). In this second approach, solar gains are simulated, based on detailed reflection algorithms, for all days of a test reference year. The results of both approaches were compared and are discussed in the subsequent section.

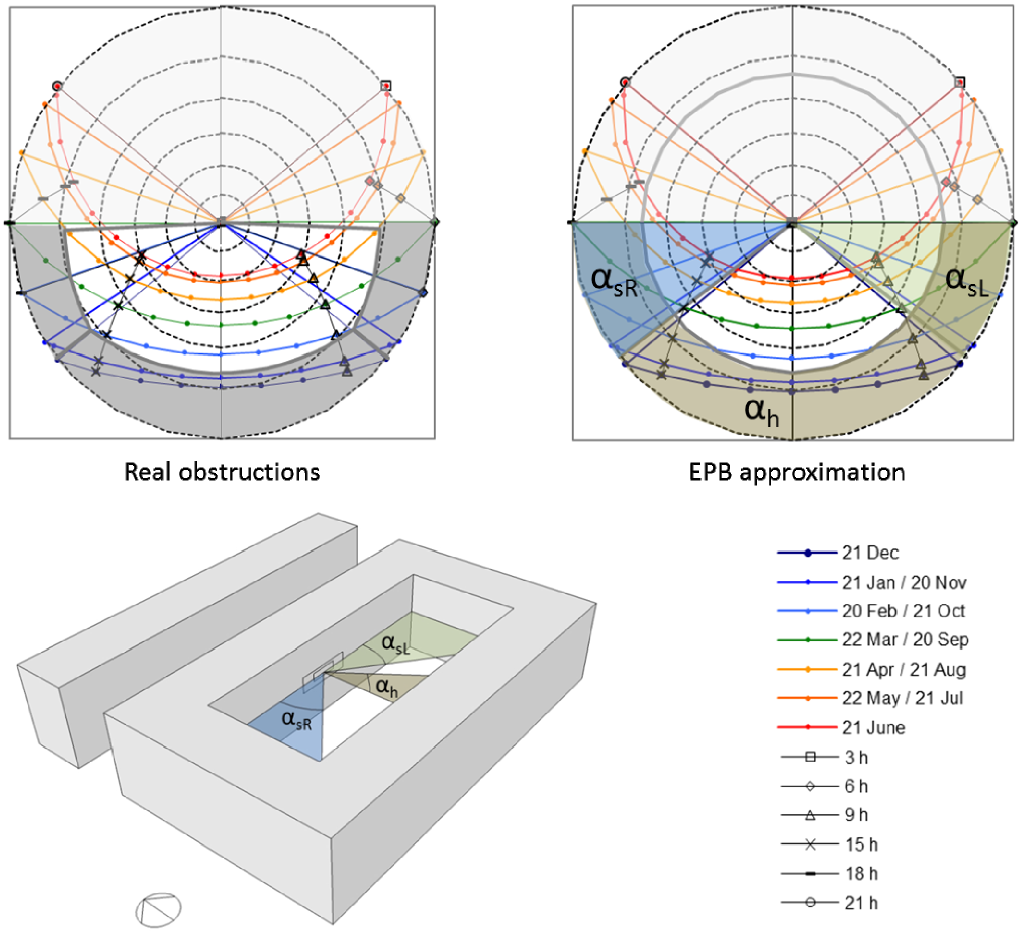

Figure 3 Stereographic projection of shading obstructions for a window in a rectangular urban block. Real obstructions (left) are compared with the EPB approximation (right).

LCA method

The environmental impact assessment in this paper is based on an existing LCA method developed within the MMG ("Milieugerelateerde Materiaalprestatie van Gebouwelementen") research project, commissioned by the Public Waste Agency of Flanders (OVAM) (Allacker et al., 2013). This method, specific for the Belgian context, evaluates the environmental performance of building elements. Besides individual impact indicators, the MMG method allows to assess the environmental impact based on an aggregated indicator, expressed in environmental costs (i.e. external costs caused by environmental impacts).

Based on the MMG database of building elements, we developed a simple tool to assess the environmental impact of buildings and neighbourhoods. Using a limited number of input data, building elements can be combined to buildings, which in turn can be clustered to a neighbourhood model. In this paper, this tool is applied for the LCA calculations.

3. SIMULATION RESULTS

Parametric model

To illustrate the methodology, we defined a parametric neighbourhood model of rectangular urban blocks (**Figure 4**), linked to the EnergyPlus software. Although many geometric variants are possible, we focus on a medium-density urban block in order to evaluate the impact of shading interactions. This block consists of 15 m high buildings around a courtyard of 50m by 20m and is separated from other blocks by 10m wide streets. In this paper, only one side of the urban block with a north-south orientation is analysed (**Figure 4**). However, the other sides could be evaluated in a similar way. For the simulations, the building is subdivided in a grid of 25 dwellings of 100m². The glazed surfaces, which are assumed to be 25% of the façades, are approximated by two big windows, oriented respectively to the street and courtyard. Futhermore, building elements, fulfilling the low energy standard, are defined, using elements from the MMG database.

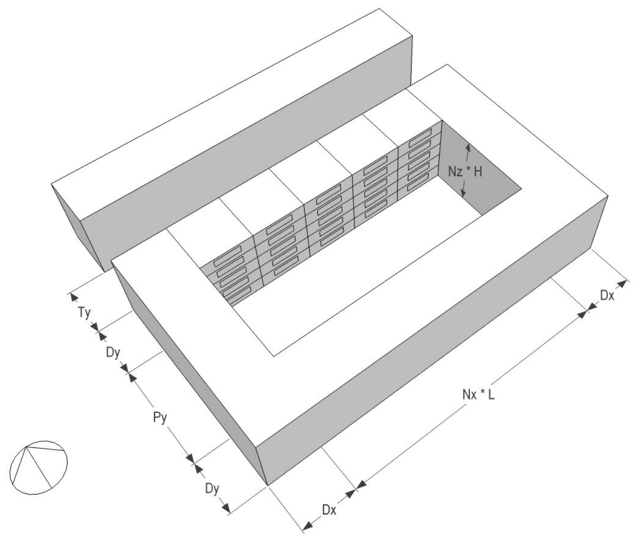

Figure 4 Parametric neighbourhood model.

Dynamic EDD calculations

For the 25 dwellings the dynamic EDD are calculated using both the EnergyPlus and EPB approach. In order to analyse the impact of shading, each dwelling is simulated both in shaded and unshaded conditions. The results are shown in **Figure 5** and expressed in percentage compared to a reference dwelling in unshaded conditions**.**

When looking at the results for the unshaded conditions, the impact of internal and solar gains is clearly noticeable in the number of EDD. As an example, the reference dwelling is characterized by 1176 eq°d based on the EnergyPlus approach (1173 eq°d based on the EPB approach), which means a reduction of about 60% of the estimated heating requirements, compared to the standard DD method (2738 °d). Furthermore, higher EDD are calculated for the dwellings located under the roof and on the ground floor. This is a consequence of the higher heat transmission losses through the building skin, resulting in lower heat gain utilization. Regarding the comparison between the semi-dynamic and dynamic approach, similar results were found, except for the dwellings on the ground floor. In this case the simplified ground heat transfer calculation in EPB seems to overestimate the heat losses via the ground.

Concerning the results in shaded conditions, an important increase of the EDD is noticed, compared to the unshaded conditions. For the EnergyPlus approach, this increase ranges from about 5% for the dwellings under the roof to about 35% for the dwellings on the ground floor. Similar results were found for the EPB approach but with bigger differences between the shaded and unshaded conditions. This is a direct consequence of the EPB approximation based on obstruction and overhang angles (**Figure 3**).

Eq d° in unshaded conditions - EnergyPlus

121%	121%	121%	121%	121%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
109%	110%	110%	110%	109%

Eq d° in unshaded conditions - EPB

121%	121%	121%	121%	121%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
123%	123%	123%	123%	123%

Eq d° in shaded conditions - EnergyPlus

125%	124%	124%	124%	125%
111%	107%	107%	107%	111%
119%	114%	113%	114%	119%
128%	125%	124%	124%	128%
143%	140%	140%	140%	143%

Eq d° in shaded conditions - EPB

131%	130%	129%	130%	131%
117%	116%	115%	116%	117%
125%	124%	123%	124%	125%
130%	129%	129%	129%	130%
150%	151%	150%	151%	150%

Figure 5 EDD of the analysed dwellings in shaded and unshaded conditions, based on the EnergyPlus and EPB approach. The results are projected on the courtyard façade and expressed in percentage, compared to a reference dwelling in unshaded conditions (indicated by the black frame).

Environmental impact calculations

Based on the calculated EDD, the heating energy consumption of the 25 dwellings can be estimated and summed up over the whole building. This total heating energy consumption can then be used as input in the LCA calculation tool. The results of the environmental impact assessment are shown in **Figure 6**, with a distinction between the impact of building materials and heating energy use. Six models to estimate the energy consumption are compared, including the standard DD method (2738°d), the static EDD using the average of 1200 eq°d and the dynamic EDD based on EnergyPlus and EPB (both for unshaded and shaded conditions).

Firstly, the results show a significant overestimation of the building environmental impact, when applying the standard DD method: the life cycle environmental costs are about 30% higher, compared to the EnergyPlus model for shaded conditions. Secondly, an average of 1200 eq°d seems a good approximation for the unshaded conditions. However, a difference of about 5% in life cycle environmental costs and about 15% in heating environmental cost was noticed between the shaded and unshaded conditions. It is expected that this difference could even be bigger, when using high-insulated passive building elements, increasing the internal utilization of solar gains. Therefore, a dynamic EDD calculation based on EPB or EnergyPlus is recommended, especially in dense neighbourhoods. Finally, only small life cycle impact differences are found between the EPB and EnergyPlus approach (from about 1% to 2% for respectively the shaded and unshaded conditions). The semi-dynamic calculation hence seems (for this case study) a good approximation for the more complex dynamic calculation.

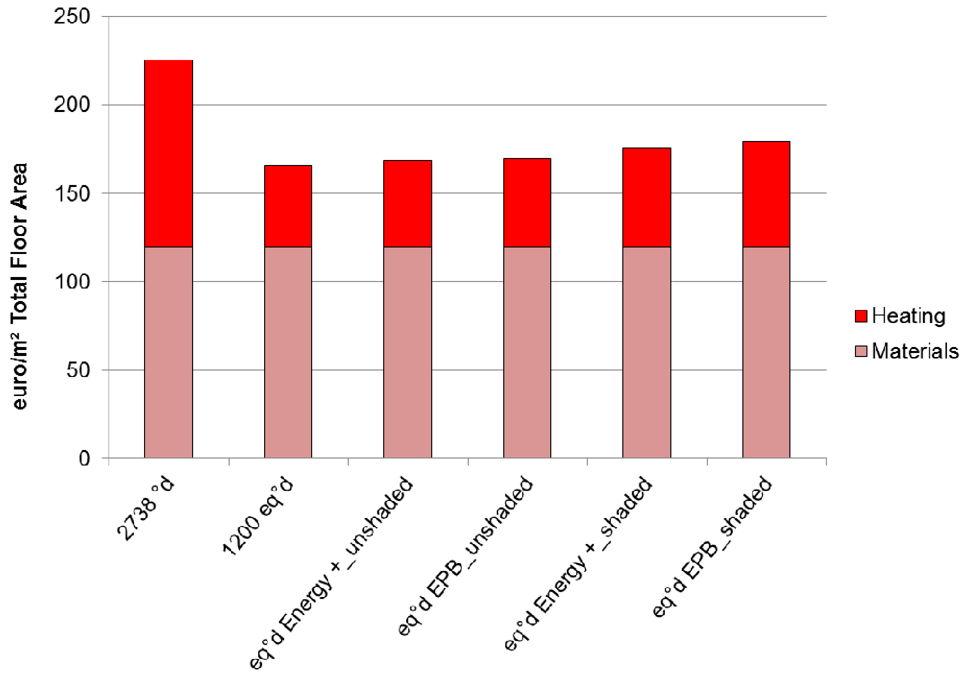

Figure 6 Building life cycle environmental cost calculated using 6 heating energy calculation methods: standard DD (2738°d), static EDD (1200 eq°d) and dynamic EDD based on EnergyPlus and EPB (for unshaded and shaded conditions).

4. CONCLUSIONS

In this paper, a simplified approach is developed to estimate the heating energy consumption in the context of neighbourhood LCA. The existing EDD method is refined by including results from both semi-dynamic and dynamic solar gain calculations. Simulations of a medium-density urban block reveal substantial heating energy demand differences between shaded and unshaded conditions, stressing the importance of more dynamic solar gain calculations, especially for dense urban developments. Nevertheless, the static EDD (1200 eq d°) seems to be a good approximation, if supplemented with dynamic EDD for the most critical housing units. Furthermore, because of limited life cycle impact differences, compared to a full dynamic simulation, the semi-dynamic EDD, based on EPB, seems to be a valuable method for integration in an LCA tool. However, to avoid an overestimation of shading patterns, it is recommended to refine the EPB approximation by using a variable obstruction angle for different orientations.

Concerning further research, we recommend validating the above conclusions by simulating more case studies and variations in urban block geometry. As the number of Equivalent Degree Days depends on the building insulation level, the influence of this parameter should be analysed in detail, especially for high-insulated passive buidlings. Finally, as the subdivision of each building block in constituting dwellings increases the simulation time, we recommend investigating whether simulations can be limited to a set of representative dwellings that could be used for interpolations.

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